

A first approach to calculate BIOCLIM variables and climate zones for Antarctica

Monika Wagner¹  • Wolfgang Trutschnig² • Arne C. Bathke² • Ulrike Ruprecht¹

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Abstract For testing the hypothesis that macroclimatological factors determine the occurrence, biodiversity, and species specificity of both symbiotic partners of Antarctic lecideoid lichens, we present a first approach for the computation of the full set of 19 BIOCLIM variables, as available at <http://www.worldclim.org/> for all regions of the world with exception of Antarctica. Annual mean temperature (Bio 1) and annual precipitation (Bio 12) were chosen to define climate zones of the Antarctic continent and adjacent islands as required for ecological niche modeling (ENM). The zones are based on data for the years 2009–2015 which was obtained from the Antarctic Mesoscale Prediction System (AMPS) database of the Ohio State University. For both temperature and precipitation, two separate zonings were specified; temperature values were divided into 12 zones (named 1 to 12) and precipitation values into five (named A to E). By combining these two partitions, we defined climate zonings where each geographical point can be uniquely assigned to exactly one zone, which allows an immediate explicit interpretation. The soundness of the newly calculated climate zones was tested by comparison with already published data, which used only three zones defined on climate information from the literature. The newly defined climate zones result in a more precise assignment of species distribution to the single

habitats. This study provides the basis for a more detailed continental-wide ENM using a comprehensive dataset of lichen specimens which are located within 21 different climate regions.

1 Introduction

The Antarctic continent with its most extreme climate conditions represents a habitat where only the hardest organisms can survive. The terrestrial biodiversity is confined to ice-free areas that actually make up only 0.34% of Antarctica (Convey 2010), and the vegetation is composed only of bryophytes and lichens with the exception of the presence of two vascular plants in the Antarctic Peninsula (Longton 1988; Peat et al. 2007). The continent itself is divided into two major vegetation zones (Peat et al. 2007). The coldest and driest areas in the world can be found in *Continental Antarctica*, comprising the main part of the continent and the eastern part of the Antarctic Peninsula. The Ross Sea region which includes extensive ice-free areas such as the McMurdo Dry Valleys (comprising about 15% of the ice-free surfaces in Antarctica; Cary et al. 2010) is one of the most important study areas for terrestrial life in cold deserts (Colesie et al. 2014b; Green 2009; Øvstedal and Smith 2001; Ruprecht et al. 2012b). By contrast, *Maritime Antarctica* includes the warmest parts of the continent, comprising the west side of the Antarctic Peninsula north of about 72° S. Additionally, Antarctica is the only continent in the world without an indigenous population, although in the last 50 years, about 30 permanent research stations have been established (Jones and Reid 2001). The whole continent has been given legal protection for scientific research (under the terms of Article 1 of the original Antarctic Treaty of 1961), which is unique on a global scale and underlines its relative pristine nature

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✉ Monika Wagner
monika.wagner@sbg.ac.at

¹ Department of Ecology and Evolution, University of Salzburg, Hellbrunnerstraße 34, 5020 Salzburg, Austria

² Department of Mathematics, University of Salzburg, Hellbrunnerstraße 34, 5020 Salzburg, Austria

(Green et al. 2011a). This continent, with the exception of highly visited coastal areas, consists of the last undisturbed wilderness and, due to its relatively simple ecosystem structure, is an ideal habitat for understanding climate-related distribution, endemism rates, detection of diversity hot spots, specificity of symbiont choice in lichens, and biodiversity research (Castello 2003; Ruprecht et al. 2012b; Seppelt et al. 1988; Wall 2005).

With increasing frequency, Antarctica becomes the focus of attention for drastic climate change scenarios like global warming and its present and future effects. These effects are discussed rather controversially, and the causal connections are still not resolved in detail. It has long been known that parts of the Antarctic Peninsula are warming rapidly (Vaughan et al. 2003), predominantly in autumn (Ding et al. 2011). Several interlinked processes have been suggested to contribute to the warming (Turner et al. 2016), including stratospheric ozone depletion (Thompson and Solomon 2002), local sea-ice loss (Turner et al. 2013), an increase in westerly winds (Marshall et al. 2006; Thompson and Solomon 2002), and changes in the strength and location of low-high-latitude atmospheric teleconnections (Clem and Fogt 2013; Ding et al. 2011). Though, since the late 1990s, some stations recorded an absence of this regional warming of the Antarctic Peninsula (Carrasco 2013). Based on ice core records studying the last 1000 years, Turner et al. (2016) suggest that both the rapid warming since the 1950s as well as the subsequent cooling is within the bounds of the large natural decadal-scale climate variability of the region. Additionally, also continental West Antarctica (comprised of Ellsworth Land and Marie Byrd Land) is affected by warming (Goosse et al. 2009; Steig et al. 2009), occurring predominantly in winter and spring (Johanson and Fu 2007; Steig et al. 2009). On the contrary, there are also reports of cooling trends of Antarctica, especially not only over parts of the high southern latitudes (summarized in Turner et al. 2005) but also, for example, for the span of the Southern Ocean between the South African coast and Antarctica (Chapman and Walsh 2007).

As mentioned above, warming trends are known to be effected by the Antarctic ozone hole (Thompson et al. 2011). The Antarctic ozone hole represents the strongest depletion of the ozone layer in the lower stratosphere and is evident since about the early 1980s (WMO 2011). It reaches its maximum extent during Antarctic spring, arising with the return of sunlight during September/October and decaying with the collapse of the stratospheric vortex during November/December (Solomon 1999; WMO 2011). As ozone absorbs incoming solar radiation, the depletion of ozone over Antarctica leads to cooling of the polar stratosphere (Randel and Wu 1999; Solomon 1999) and then, in turn, to an acceleration of the stratospheric polar vortex (a region of strong eastward circumpolar flow) during October–December (Waugh et al. 1999). The latter is coupled to variability in

the tropospheric flow in the form of Southern Annular Mode (SAM), the principal mode of variability in the Southern Hemisphere, which has a large impact on the climate of Antarctica (Marshall 2016). However, the mechanisms of the linking between the polar vortices and the SAM are not fully understood, yet (Thompson et al. 2011).

The terrestrial biota in Antarctica generally is concentrated in hypolithic, endolithic, chasmolithic, and soil communities formed of microorganisms mainly including bacteria, fungi, and algae, as well as springtails, mites, and nematodes close to meltwaters and a macrovegetation of lichens and mosses (Peat et al. 2007). Various studies in the past dealt with biodiversity and/or ecogeographic distribution in bacterial (e.g., Bottos et al. 2014), hypolithic (Khan et al. 2011), and endolithic communities (Yung et al. 2014); soil crusts (Colesie et al. 2014a), mosses (Schroeter et al. 2011), or lichens (e.g., Castello 2003; Green et al. 2011b; Hertel 2007; Øvstedal and Smith 2001; Ruprecht et al. 2010; Ruprecht et al. 2012b) as well as macroflora in general (Peat et al. 2007); springtails, mites (McGaughan et al. 2008; Stevens et al. 2006), and nematodes (Adams et al. 2014). Most of these terrestrial biodiversity studies were conducted along the latitudinal gradient at the Ross Sea coastline. Interestingly, no latitudinal gradient in biodiversity of lichens and mosses occurs in the Ross Sea region, which was explained by terrestrial vegetation being confined to microhabitats (Colesie et al. 2014b; Green et al. 2011a). But to date, the similarities of the areas in terms of macroclimate conditions were not investigated, mainly due to the lack of area covering climate data for Antarctica. Several studies show clear differentiation in species composition on lichen photobionts, which are evidently climate related (Fernandez-Mendoza et al. 2011; Jones et al. 2013; Peksa and Skaloud 2011; Ruprecht et al. 2012a) and match well with the macroclimate conditions.

However, for large-scale niche modeling projects which require two types of data, accurate latitude/longitude coordinates (i.e., georeferenced localities) and environmental data available in form of GIS layers, no sufficient continent covering climate data was available. Although a number of research stations exist with climate records covering the last decades as well as automatic weather stations from different projects that are positioned in several localities (<http://amrc.ssec.wisc.edu/aws/>), this information is merely useful for the specific location and too sophisticated to be exploited by a non-specialized user. Several attempts have been made to define Antarctic zones of climatological or environmental variables, but none of them has been published yet or provides data sets for other users. In 2007, the Department of Conservation of the New Zealand Landcare Research established environmental domains of Antarctica, based on mean annual air temperature,

seasonal air temperature range, mean annual wind speed, estimated solar radiation at top of atmosphere, period of year with normal diurnal pattern, slope, land (ice) cover, and geologic information (Morgan et al. 2007). Unfortunately, the data does not include precipitation, and the high number of variables makes it difficult to interpret the single zonings. There is also a Russian comment in this study, where the authors briefly discuss their own biogeographic regions (http://www.ats.aq/documents/ATCM36/wp/ATCM36_wp022_e.doc), but further information about this classification could not be found. Since 1996, the Phytosociological Research Center and the University Complutense of Madrid have run a worldwide bioclimatic classification system, in the course of which they also uploaded different classifications of Antarctica, namely based on bioclimates, thermotypes, ombrotypes, and continentality (Rivas-Martinez et al. 2010). In general, this classification would be quite suitable, but unfortunately, the differentiation of the several areas is too coarse for our purpose—most of our lichen samples would be located in one and the same zoning.

For our requirements, none of the classifications were suitable for the specific demands of our studies (not least because the underlying data is not available). The huge Antarctic continent can only be covered by modeled and coherent data to provide a useful map of macroclimate zones for consequent niche modeling, essential for biogeographic and population genetic research. The first package for species distribution modeling was BIOCLIM, conceived in 1986 by Henry Nix (1986) who also led the development of the package (Booth et al. 2014). Since then, a number of significant steps have improved the concept and methods, and now, the WorldClim database (Hijmans et al. 2005) represents the most common source of climate data for such kind of modeling, as it offers downloadable climatic data for 19 different BIOCLIM variables. The climate surfaces of the WorldClim database cover all of the global land areas, excluding Antarctica. Thus, in the present study, we computed Antarctic BIOCLIM variables as established by Hijmans et al. (2005) and adapted defined climate zones. This was done by using temperature and precipitation data from the real-time implementation of the Weather Research and Forecasting model database Antarctic Mesoscale Prediction System (AMPS, Skamarock et al. 2008) which is currently a collaboration of the National Center for Atmospheric Research (NCAR) and the Polar Meteorology Group of the Byrd Polar Research Center at the Ohio State University (Powers et al. 2012). AMPS began in 2000 and has undergone several improvements and upgrades since then (for studies about the verification of AMPS data, see Powers et al. 2012). Both of our data sets (BIOCLIM variables as well as climate zones) are

freely available and applicable for all other broad-scale biodiversity studies where climate data based on temperature and precipitation are required.

The present study is an important contribution to a current research project (Diversity, ecology, and specificity in Antarctic lichens) to search for evidence that variations in Antarctic macroclimate may control the distribution of photobionts and/or mycobionts in the all over the continent available crustose lecideoid lichens and possibly the specificity of (certain) mycobionts towards the photobionts (Ruprecht et al. 2012a). There have been several studies dealing with this climate-dependent specificity between mycobiont and photobiont (e.g., Fernandez-Mendoza et al. 2011; Jones et al. 2013; Peksa and Skaloud 2011; Ruprecht et al. 2012a). In our study, we aim to define the base for the modeling and comparison of the Antarctic climatic conditions, in order to show preferences of each symbiotic partner (photobiont vs. mycobiont) identified within given lichen samples. To accomplish this goal, we defined climate zones for comparing and classifying Antarctic lecideoid lichen samples.

2 Materials and methods

For all calculations and graphics, we used the free statistical software environment R (R Core Team 2015).

Besides the calculation of the 19 BIOCLIM variables for Antarctica (see end of this section), this study focuses on two of the BIOCLIM variables, namely annual mean temperature (Bio 1) and annual precipitation (Bio 12). However, we decided to not use Bio 1 and Bio 12 themselves for the definition of the climate zonings but to calculate annual mean temperature and annual precipitation manually, to get temperature data based on the monthly averages and not on the monthly minimum and maximum values (as Bio 1 usually is computed).

2.1 Data preparation

The following preliminary steps were required: (1) processing of the original data, (2) computation of annual 2009–2015 data, (3) coordinate transformation and reduction to terrestrial points, and (4) averaging of 2009–2015 data.

2.2 Processing of the original data

Climate data for Antarctica were downloaded from the AMPS; a repository of this model forecast output is the AMPS archive (Powers et al. 2012). Basic variables are available at <http://polarmet.osu.edu/AMPS/>. The database offers different domains with different image sections and horizontal resolutions. In this study, we analyzed three different domains: domain 2 (d2, whole Antarctica),

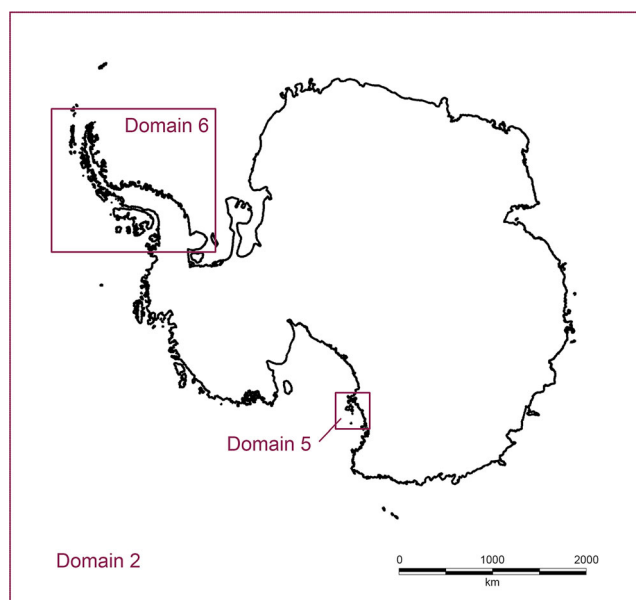


Fig. 1 The three Antarctic domains that were used in this study (labeling according to the AMPS database <http://polarmet.osu.edu/AMPS/>)

domain 5 (d5, Dry Valleys), and domain 6 (d6, Maritime Antarctica) (Fig. 1). Two parameters covering 7 years (2009–2015) were used, both of them in the form of three hourly forecast data: temperature at the surface (in Kelvin) and 3 h accumulated precipitation (in kg/m^2). The spatial resolutions as well as the image sections of the three domains differed within these 7 years (Table 1). Thus, to get uniform resolutions of 10 km (d2), 1 km (d5), and 3 km (d6), respectively, the data was interpolated (details see below). The years before 2009 were not taken into account because the resolution of 20 km (in d2) was insufficient for the tasks of this study.

The calculated climate zones are focusing on climatic requirements for terrestrial life, especially on the habitats of the more than 500 lecideoid lichen specimens from different ice-free areas all over the Antarctic continent and adjacent islands which are included in the overall project. Figure 2 shows a

Table 1 Differences in horizontal resolution and image section of the AMPS data used in this study

	Years	Horizontal resolution (km)	Grid points of image section
d2	2009–2012	15	442 × 418
	2013–2015	10	666 × 627
d5	2009–2012	1.67	214 × 229
	2013 (01–05)	1	324 × 345
	2013 (06–12)–2015	1	613 × 718
d6	2009–2012	5	346 × 301
	2013–2015	3	519 × 453

relief map with the location of the collection sites in d2 (a), d5 (b), and d6 (c).

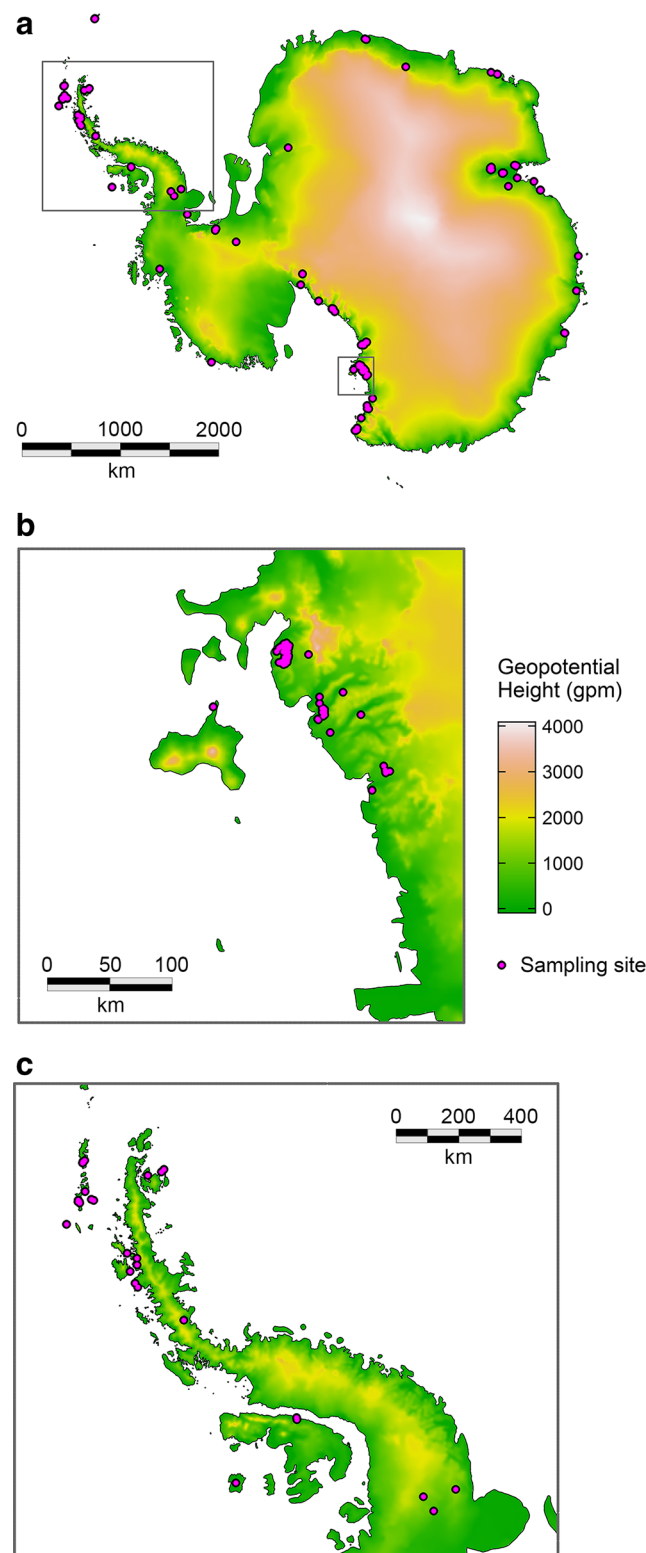


Fig. 2 Location of lichen sampling sites within Antarctic d2 (a, 528 samples), d5 (b, 217 samples), and d6 (c, 52 samples)

Table 2 Days whose original data were replaced by averaging daily means of the previous and subsequent days

Month	Domain	2009				2010				2011	2012	2013	2014	2015
Jan.	d2, d5	–				–				26	–	–	–	–
	d6	–				–				26	–	1 ^a	–	–
Feb.	d2	27				–				12	–	–	–	–
	d5, d6	27				–				12	–	7	–	–
Mar.	d2	–				12				–	–	–	–	–
	d5, d6	–				–				–	–	–	–	–
Apr.	d2, d5, d6	4	5	18	25	4	10			9	–	–	–	–
May	d2, d6	4				–				–	–	–	13	–
	d5	4				–				–	–	31	13	–
Jun.	d2, d6	–				26				13	–	–	14	–
	d5	–				11	26			13	–	–	–	–
Jul.	d2	2	16	18	19	23	25	26	27	13	14	15	–	–
	d5	2	16	18	19	22	25	26	27	13	14	15	28	–
	d6	2	16	18	19	22	25	26	27	13	14	15	–	–
Aug.	d2, d5	–				7	19			–	–	–	–	–
	d6	–				7	19	9		–	–	–	–	–
Sept.	d2, d5, d6	–				10				19	–	–	23	–
Oct.	d2, d5, d6	17				9				15	20	–	–	–
Nov.	d2, d5, d6	27				1	3			–	12	–	–	–
Dec.	d2, d5, d6	–				11				–	31	–	–	–

Asterisk indicates that only precipitation (not temperature) data was incomplete and therefore replaced

2.3 Computation of annual 2009–2015 data

For computing the annual mean temperature and annual precipitation, first of all, monthly values were determined. The whole data set of a single month (for example, 248 files for January, corresponding to eight three hourly forecasts a day) was loaded in R (using `nc_open()` in the R package `ncdf4`; Pierce 2015), averaged (in case of temperature data) or rather summed up (precipitation data), and saved as new files. Those 12 monthly files of a single year were then averaged and summed up respectively to get annual data.

In the original data for precipitation, negative values can occur, due to the fact that the data of AMPS arise from computations. Negative values were substituted by zeros in this study.

During the process of computing monthly data, we had to deal with the problem of missing values. Sometimes, all the eight forecasts of a day were missing, sometimes only a few of them. We decided to delete all the data of a single day if it was incomplete and to replace the values (by averaging daily means of the previous and subsequent days) which does not distort the overall data. Table 2 summarizes the replaced data.

2.4 Transformation to an orthogonal grid and reduction to terrestrial points

The AMPS data files contain not only terrestrial points of the Antarctica but also points of the adjacent marine area (and ice

shelves). Thus, the next step was to reduce the data to terrestrial points.

The country borders of Antarctica were downloaded from <http://www.gadm.org/download>. The coordinate reference system of this data set is WGS84 decimal degrees. These coordinates of the Antarctic borders were converted into projected Cartesian coordinates, which was done by applying a stereographic projection using the R function `mapproject()` in the package `mapproj` (McIlroy 2015) (Fig. 3).

The coordinate reference system of the AMPS data is also in WGS84 decimal degrees. Application of the stereographic projection on the AMPS longitude and latitude data resulted in a spatial grid with angles that were not exactly orthogonal, which, however, is necessary for using, for example, the R plotting function `geom_tile()` in the package `ggplot2` (Wickham 2009). Thus, a grid was created which had the same coordinate minimum and maximum values and the same number of grid points as the previous grid, but with orthogonal angles. This was done for all three domains, in each case choosing the highest definition (10 km for d2, 1 km for d5, and 3 km for d6). After reducing this new orthogonal grid (containing, for example, 417,582 data points in d2) to those points lying within terrestrial Antarctica (121,670 data points in d2), the annual temperature means and the annual precipitation on the aforementioned grid were calculated by interpolation. This was done by ordinary kriging, using the R function `krige()`

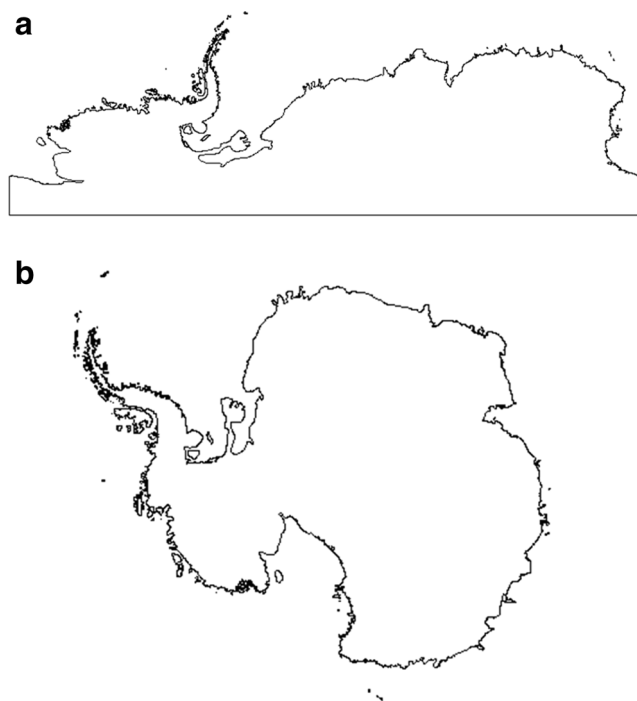


Fig. 3 Antarctic borders before (a) and after (b) the coordinate transformation (stereographic projection)

in the package *gstat* (Pebesma 2004). All data was given on the same grid. Any negative precipitation values were again replaced by zeros.

2.5 Averaging of 2009–2015 data

Subsequently, the 2009–2015 data was averaged. Therefore, for each of the three domains, we gained two data sets: one of the annual mean temperature and one of the annual precipitation.

To evaluate our data, annual mean temperatures for 30 different climate stations were determined by interpolation and compared to data from literature. With the exception of Hallett station, data was taken from the website of the

Databank of Antarctic Surface Temperature and Pressure Data (Jones and Reid 2001) of the Carbon Dioxide Information Analysis Center (CDIAC). Hallett data is from the Latitudinal Gradient Project website (<http://www.lgp.aq>).

2.6 Correlation coefficients

To determine correlations between climate variables (annual mean temperature, annual precipitation, BIOCLIM variables) and geological variables (latitude, elevation, distance to coast), several computations were necessary: For the correlation with latitude and elevation, the original latitude (not transformed by stereographic projection) and elevation data was interpolated to the orthogonal grid, as done before for temperature and precipitation data. The distance to the coast was calculated using the R function *gDistance()* in the package *rgeos* (Bivand and Rundel 2016). Correlations were calculated using *cor.test()* in the R package *stats* (R Core Team 2015), which also includes a test of the value being zero.

2.7 Definition of climate zones

For both temperature and precipitation, separate zonings were constructed, respectively. Subsequently, these two zonings were combined to define climate zones.

2.8 Definition of temperature zones

Initially, the temperature data of d2 was divided into three zones by standard *k*-means clustering using the R function *kmeans()* in the package *stats* (R Core Team 2015). Nearly all of our lichen samples happened to be located in the “warmest” third, only a few in the middle, and none in the coldest one. Thus, to get a finer partitioning of the temperature zone relevant for our studies, the warmest third was evenly divided into ten subzones. The warmest zone was assigned

Table 3 Range of the kriging standard deviations derived from the single interpolation steps of the different data sets

	Annual mean temperature (°C)			Annual precipitation (mm)		
	d2	d5	d6	d2	d5	d6
2009	1.39	6.74×10^{-1} –1.23	6.84×10^{-1} – 7.59×10^{-1}	110.48–110.92	0.37–53.29	13.57–192.02
2010	1.48	6.69×10^{-1} –1.32	7.09×10^{-1} – 7.84×10^{-1}	134.39–134.81	0.11–42.38	7.03–258.02
2011	1.47	8.83×10^{-3} –1.31	7.00×10^{-1} – 7.86×10^{-1}	120.81–121.22	0.52–75.45	107.70–206.26
2012	1.51	6.40×10^{-1} –1.59	8.02×10^{-1} – 8.87×10^{-1}	108.09–108.65	3.99–51.21	14.86–210.26
2013	1.78×10^{-6} – 3.25×10^{-4}	3.92×10^{-1} – 4.00×10^{-1}	7.55×10^{-1} – 7.66×10^{-1}	120.60	9.30–9.32	79.30–80.62
2014	1.35×10^{-6} – 3.28×10^{-4}	5.52×10^{-1}	7.72×10^{-1} – 7.81×10^{-1}	119.99	30.01	106.78–108.28
2015	$\leq 1.18 \times 10^{-3}$	6.14×10^{-1}	8.25×10^{-1} – 8.36×10^{-1}	102.01	25.63–25.64	103.20–104.65

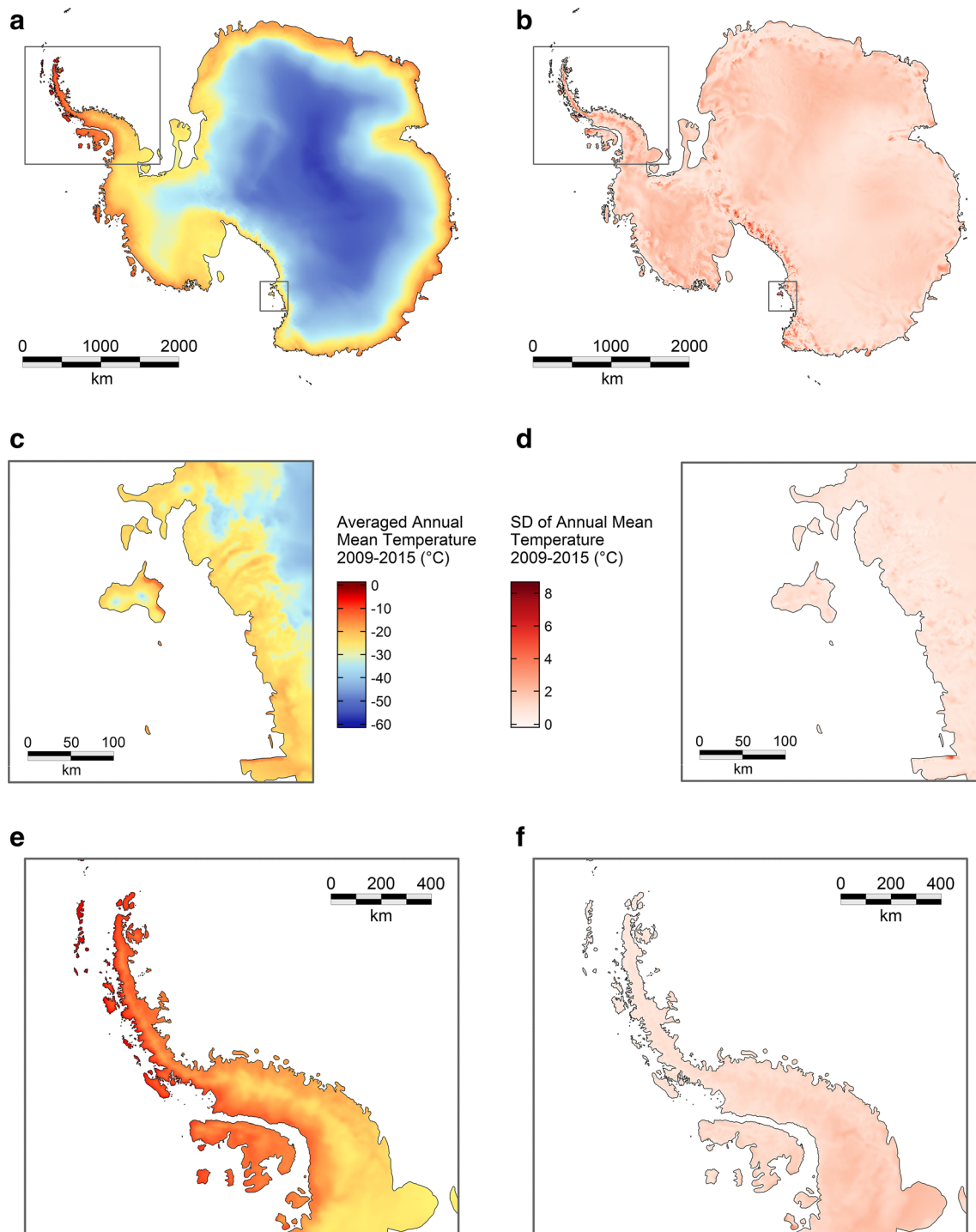


Fig. 4 Averaged annual mean temperature values (a, c, e) and SDs (b, d, f) of Antarctic d2 (a, b), d5 (c, d), and d6 (e, f)

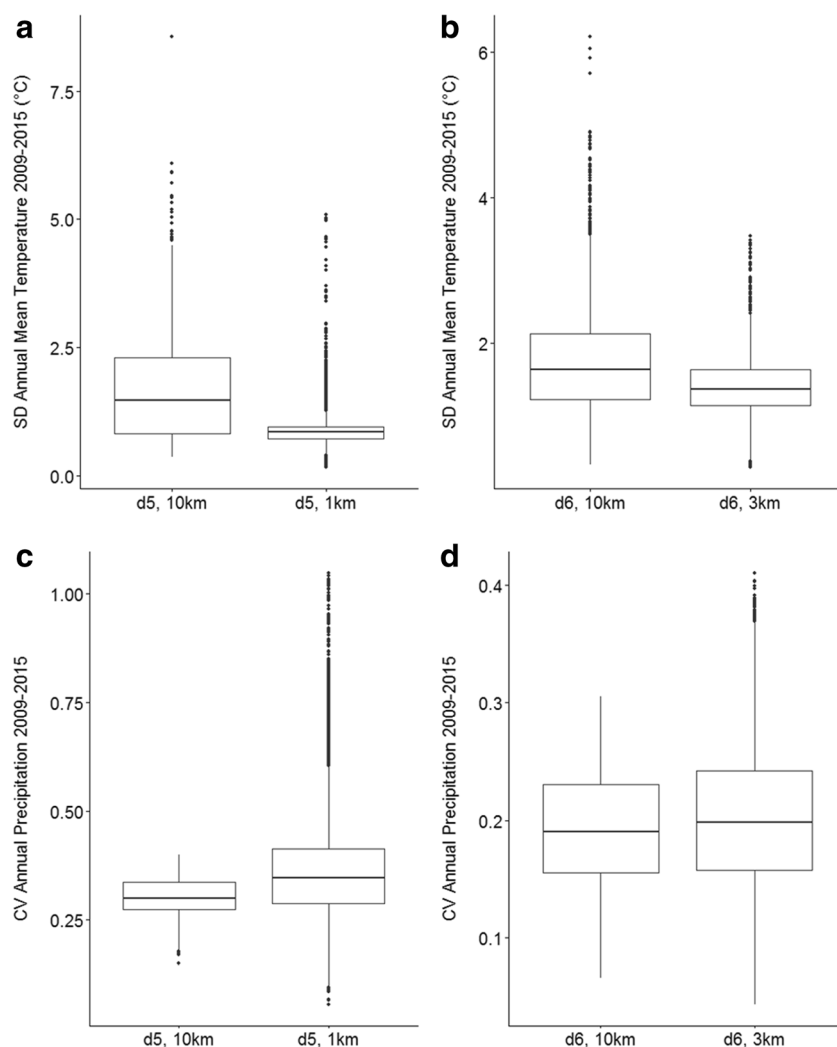
zone number 1, the coldest zone number 12. We partitioned the regions d5 and d6 using the same zoning (based on d2).

2.9 Definition of precipitation zones

The precipitation zones were defined following the concept of Meigs (1953) who established the classification of

hyperarid (<25 mm), arid (25–200 mm), and semiarid (200–500 mm) deserts (Meigs 1953). To get a finer partitioning, precipitation values above semiarid were about evenly divided into two zones. The zone with the highest precipitation was named A and the zone with the lowest precipitation, E. Regions d5 and d6 were partitioned based on the same precipitation ranges.

Fig. 5 Comparison of the annual mean temperature SDs (**a**, **b**) and annual precipitation CVs (**c**, **d**) in different horizontal resolutions: image section of Antarctic d5 (**a**, **c**) and d6 (**b**, **d**)



2.10 Definition of climate zones

Following the separate definition of temperature and precipitation zones, the two classifications were then combined. As direct consequence, each grid point of Antarctic d2, d5, and d6 was assigned a number (from 1 to 12) and a letter (from A to E). The arising concept of theoretically 60 different climate zones seems confusing at a first glance; the dual nomenclature, however, allows for a straightforward, quick, and accurate interpretation.

2.11 BIOCLIM variables

The 19 BIOCLIM variables were computed as established by Hijmans et al. (2005). In a first approach, we used all the variables for the definition of the climate zones. The inclusion of multiple variables led to zonings overlapping

in single variables; for example, climate zone A with higher mean precipitation than zone B also included points with lower precipitation values. However, the zonings only differed in the mean values but not in the boundary points of a single BIOCLIM variable. Thus, in order to avoid problems caused by multicollinearity, we decided to reduce the zone definition to only two parameters, which allows easier comparison of locations.

The BIOCLIM variables were computed using the R function `biovars()` in the R package `dismo` (Hijmans et al. 2016). The computation requires monthly minimum and maximum temperature values as well as monthly precipitation data. By computing the monthly temperature means (see above), monthly temperature minimum and maximum values were calculated in the same step. Those monthly values then were averaged over the years 2009–2015. Precipitation data was calculated in a similar way.

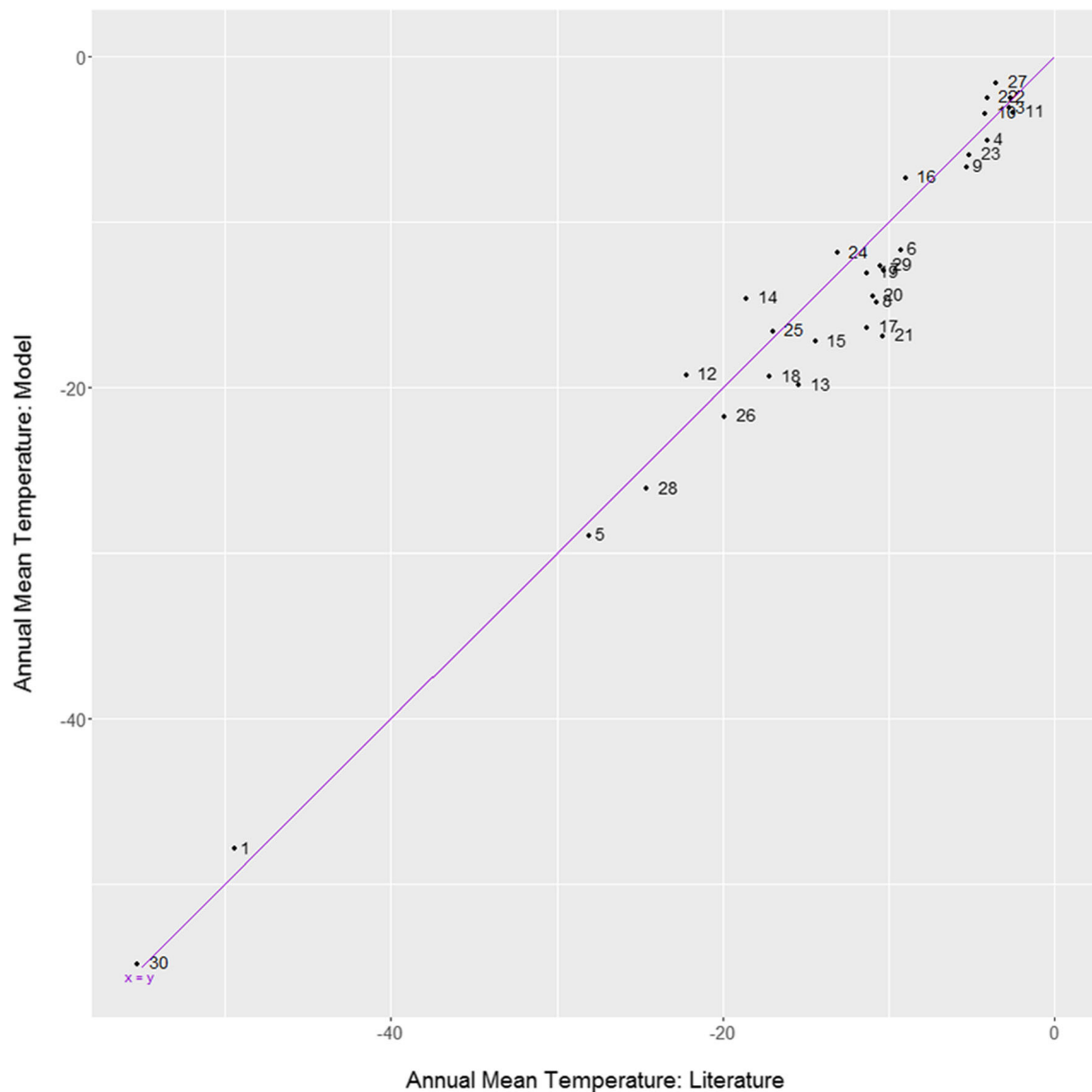


Fig. 6 Annual mean temperature data of our model as a function of temperature data from literature for Antarctic meteorological stations; numbers indicate station IDs: Amundsen-Scott (1), B.A. Arturo Prat (2), Bellingshausen (3), Bernardo O'Higgins (4), Byrd (5), Casey (6), Davis (7), Dumont d'Urville (8), Esperanza (9), Faraday (10), Frei (11), General Belgrano (12), Hallett (13), Halley Bay (14),

Leningradskaja (15), Marambio (16), Mawson (17), McMurdo (18), Mirny (19), Molodznaja (20), Novolazarevskaja (21), Orcadas (22), Rothera (23), Russkaya (24), Sanae (25), Scott (26), Signy Island (27), Siple (28), Syowa (29), and Vostok (30). Numbers 18 and 26 are located within d5; 2, 3, 4, 9, 10, 11, 16, and 23 are located within d6

2.12 Testing the soundness of the newly calculated climate zones vs. three climate zones defined by heterogeneous data from literature

Ruprecht et al. (2012a) investigated the photobiont diversity and abundance of lecideoid lichens from several localities in continental and maritime Antarctica. Focused on the photobiont diversity, they subsequently identified five major *Trebouxia* clades and correlated their occurrences with the climatological features of the sample sites. Based on literature

data, they defined three different Antarctic climate types (dry and cold, intermediate, humid and relatively warm) based on heterogeneous information from the literature and classified the *Trebouxia* clades according to them.

Compared to the study from 2012, the same 98 Antarctic lichen samples were reclassified according to the newly generated climate zones. To achieve this, the Bio 1 and Bio 12 values were interpolated to the sample locations and subsequently assigned to the temperature and precipitation zones as described above. The samples belonged to five different

Trebouxia species, namely *Trebouxia jamesii* (12 samples, 6 of them forming a subclade), *Trebouxia* sp. URa1 (8 samples), *Trebouxia impressa* (9 samples), *Trebouxia* URa2 (42 samples), and *Trebouxia* URa3 (26 samples).

3 Results

3.1 Data preparation

Standard deviations derived from the kriging procedure are shown in Table 3.

Averaging the annual mean temperatures for the years 2009–2015 of d2 resulted in values between -57.27 and -0.88 °C with standard deviations (SDs) between 0.31 and 8.70 °C. The temperature averages of d5 ranged from -43.62 to -12.64 °C with SDs between 0.16 and 5.09 °C, while d6 averages lay between -27.94 and -0.78 °C with SDs between 0.30 and 3.47 °C (Fig. 4). For d5 and d6, we compared the SDs with those of the same image section using the d2 data (with a horizontal resolution of 10 km instead of 1 and 3 km, respectively). The comparison showed a decrease of variation when using higher resolution (Fig. 5a, b).

The comparison of interpolated temperature data from this study and reference data from literature is shown in Fig. 6: For 11 stations, our model suggests higher and for the other 19 stations lower temperature values. The maximal deviation of the literature to the model data amounts to 6.60 °C (Novolazaravskaja, number 21), the minimal deviation -0.15 °C (B.A. Arturo Prat, number 2), the average deviation 1.02 °C, and the average absolute difference 2.11 °C. The average absolute difference for those stations located within d5 (numbers 18 and 26) and d6 (numbers 2, 3, 4, 9, 10, 11, 16, and 23) amounts to 1.12 °C. The Pearson's correlation coefficient between annual mean temperature and latitude values of the 30 stations was 0.85.

Averaging the annual precipitation for the years 2009–2015 of d2 resulted in values between 1.35 and 4399.17 mm per year with SDs between 0.72 and 797.25 mm. The precipitation averages of d5 ranged from 4.09 to 1378.43 mm with SDs between 1.68 and 285.42 mm. D6 averages lay between 122.94 and 7431.12 mm with SDs between 15.96 and 1307.17 mm. Coefficients of variation (CVs) were also computed for annual precipitation and ranged between 0.04 and 1.08 at d2, between 0.06 and 1.05 at d5, and between 0.04 and 0.41 at d6 (Fig. 7). For d5 and d6, CVs were compared with those of the same image section using the d2 data (with a horizontal resolution of 10 km instead of 1 and 3 km, respectively). In this case, the comparison showed a slight increase of this standardized variation measure when using finer resolution (Fig. 5c, d).

The correlation coefficients between the climate variables and the geographical parameters are shown in Fig. 8. Nearly all the correlations are significantly different from zero, with p values <0.01 (except for Bio 3 vs. latitude d5; p value 0.013). In d2, most of the correlation coefficients of latitude and the climate variables are around ± 0.4 . Region d5 shows a smaller correlation with the climate variables in contrast to latitude d6 which shows some very high correlations. Elevation d2 and distance to coast in d2 exhibit a similar pattern of correlation coefficients, which may be due to the fact that those two factors correlate with a coefficient of 0.85. Within d2, elevation shows the strongest correlation with the climate variables, above all a negative correlation with those variables comprising annual mean, minimum, or maximum temperature data (annual mean temperature/Bio 1, Bio 5, Bio 6, Bio 9, Bio 10, and Bio 11). Elevation in d2 also has a strong positive correlation with Bio 7, whereas it negatively correlates with those climate variables based on annual precipitation (but those values do not fall below -0.60). Regarding d5, the correlation coefficients of elevation and the climate variables based on temperature are quite similar to d2, except those regarding elevation and precipitation climate variables which are around zero. In d6, the correlation values between elevation and climate variables are much lower in general; only Bio 5 and Bio 10 are below -0.69 .

Note: annual mean temperature corresponds to Bio 1 and annual precipitation to Bio 12; nonetheless, while the annual mean temperature was determined by the calculation of “real” means, Bio 1 is based solely on minimum and maximum values. For annual precipitation, the annual sums of 2009–2015 were interpolated to the orthogonal grid and averaged afterwards (only one interpolation process), while Bio 12 is based on *monthly* means of 2009–2015 that were interpolated after averaging (one interpolation process for every month). These differences in computation explain the differences in the correlation coefficients.

3.2 Definition of climate zones

The temperature and precipitation ranges of the 12 temperature and 5 precipitation zones are shown in Table 4.

Assigning the annual mean temperature values of d5 to the 12 temperature zones constructed for d2 resulted in the occurrence of 8 temperature zones (zone number 5 to number 12) within this region; the values of d6 corresponded to the temperature zones 1 to 10. Regarding the precipitation zones, all five zones are present in d5, and only four are present in d6 (Fig. 9).

A combination of the 12 temperature zones and the 5 precipitation zones is depicted in Fig. 10. Of the 60 possible combinations, only 46 actually occurred (Table 5).

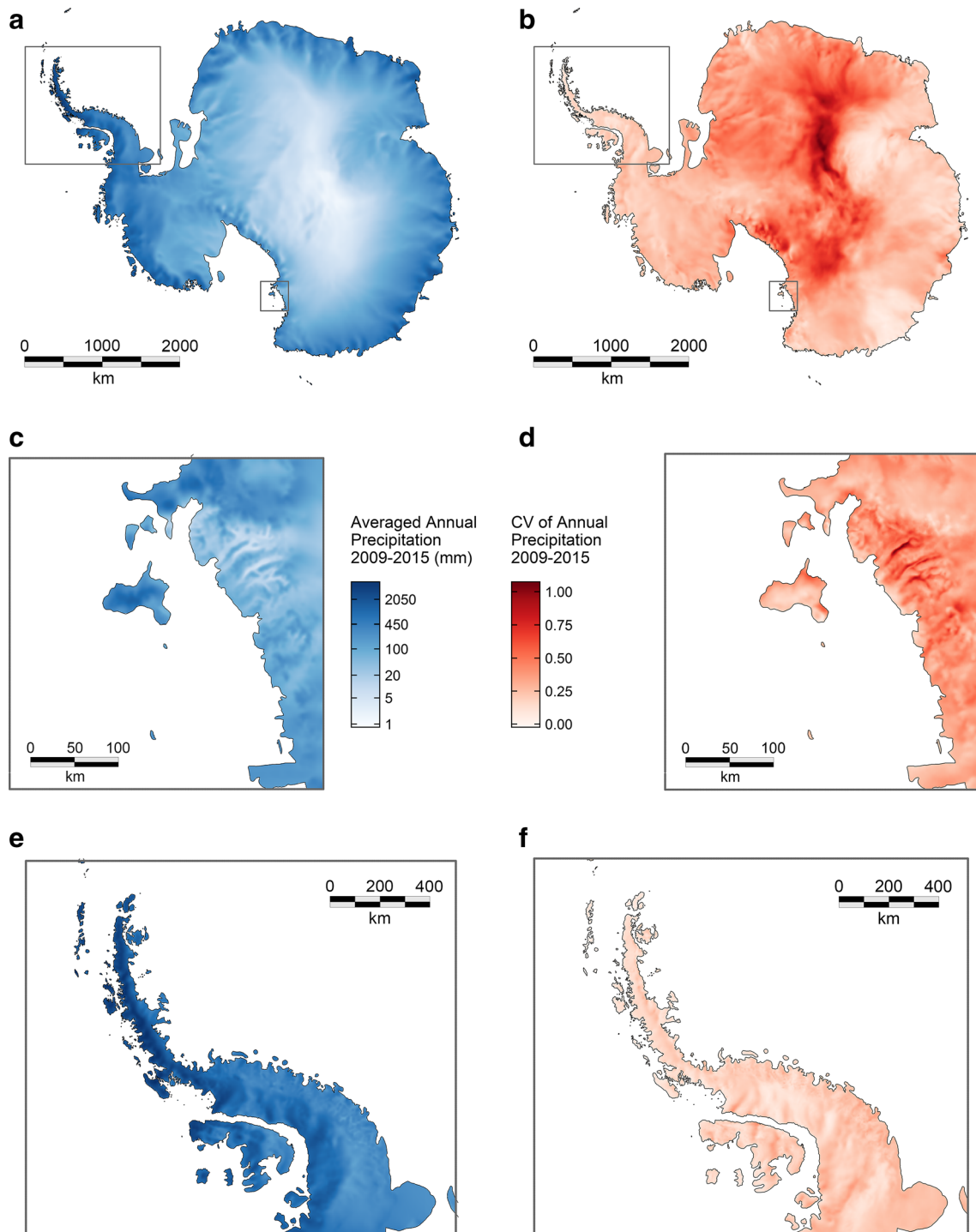


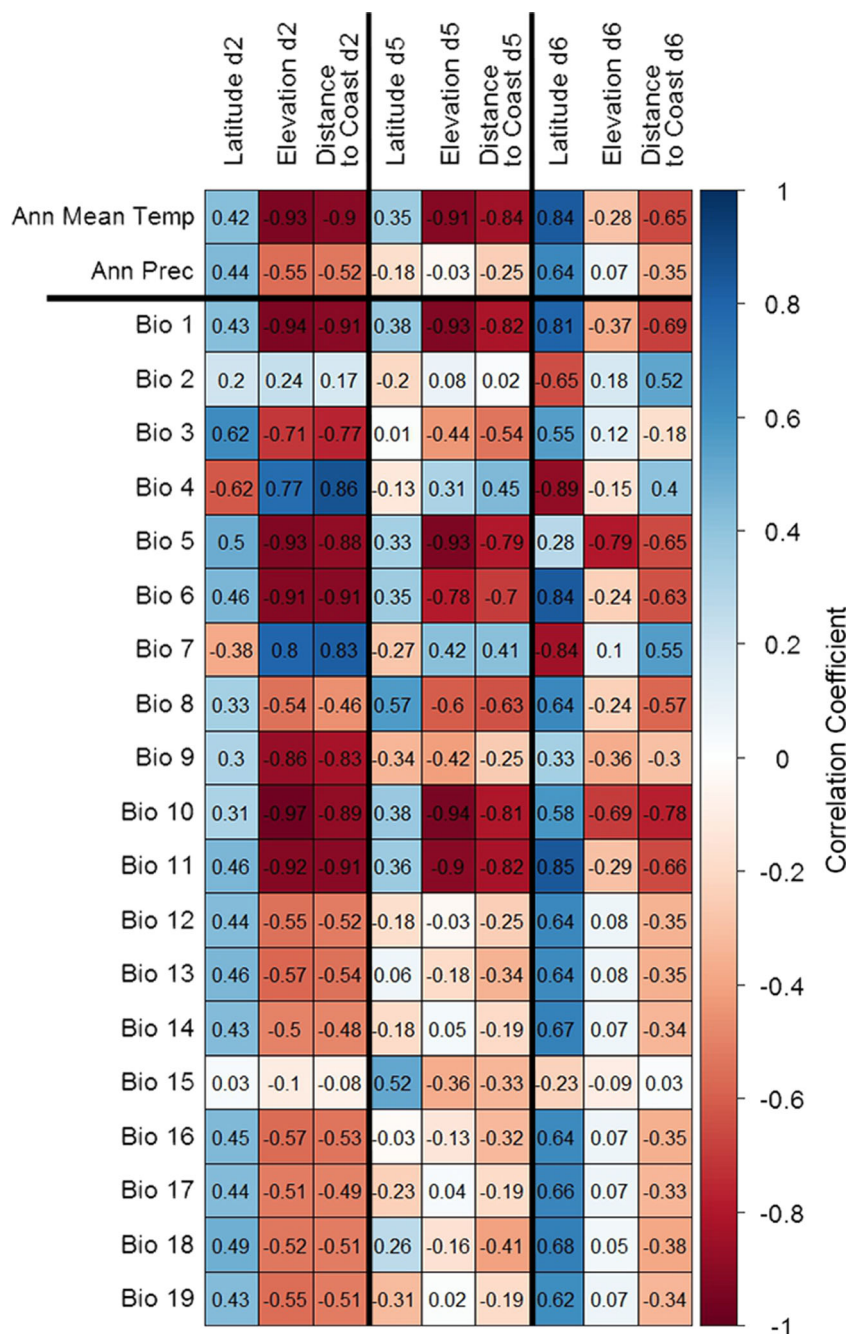
Fig. 7 Averaged annual precipitation values (a, c, e) and CVs (b, d, f) of Antarctic d2 (a, b), d5 (c, d), and d6 (e, f)

The distribution of the lichen samples within the different climate zones was quite scattered. All together, we had 528 lichen samples, of which 217 were located in d5 and 52 in d6. The samples were located in temperature zones 1 to 11 and in precipitation zones A to D. The distribution and frequency is shown in Fig. 11.

3.3 BIOCLIM variables

The annual mean temperature, the annual precipitation, and the 19 BIOCLIM variables for Antarctic d2, d5, and d6 are available for download at <http://www.uni-salzburg.at/index.php?id=204924>. The data format is geoTiff.

Fig. 8 Pearson correlation coefficients between climatic (annual mean temperature, annual precipitation, BIOCLIM variables) and geological variables (latitude, elevation, distance to coast) for Antarctic d2, d5, and d6



3.4 Testing the soundness of the newly calculated climate zones vs. three climate zones defined by heterogeneous data from literature

The classification of the *Trebouxia* sample sites is shown in Fig. 12. For the comparison of this study and the study of Ruprecht et al. (2012a), it is important to notice that the latter also included samples from South America, Europe, USA, and Arctic, which was not done here. All together, they described

six different climate zones, of which only the first three were restricted to Antarctica and thus also mentioned here. Ruprecht et al. (2012a) described some tendencies which in the main also appear in the classification of the present study: *T. jamesii* seems to be rather variable regarding climate (their samples occurred in all the six climate zones), but the (exclusively Antarctic) subspecies only occurs in cold and dry areas. *T. sp. URa1* appears only in very cold and dry environments, while *T. sp. URa3* is rather widely distributed. *T. sp. URa2* is described

Table 4 Range of the temperature and precipitation values in the different zones

Temperature zones		Precipitation zones	
1	>−3 °C	A	>1000 mm
2	−6 to −3 °C	B	500–1000 mm
3	−9 to −6 °C	C	200–500 mm
4	−12 to −9 °C	D	25–200 mm
5	−15 to −12 °C	E	<25 mm
6	−18 to −15 °C		
7	−21 to −18 °C		
8	−24 to −21 °C		
9	−27 to −24 °C		
10	−30 to −27 °C		
11	−43 to −30 °C		
12	<−43 °C		

to be not found in extremely cold and dry environments, something that is not supported by our classification.

4 Discussion

In general, a reasonable climate zoning for an effective ecological niche modeling on, e.g., lichen specification, should satisfy the following requirements: It should be simple, easily and quickly comprehensible, and reproducible, and it should contain the main variables of interest for the investigated organism. Above all, it has to reflect the characteristics of the underlying data in an appropriate way.

The temperature distribution depicted in Fig. 4 and the precipitation distribution in Fig. 7 in general suggest warmer and wetter habitats towards the coast line, with peak values at the Antarctic Peninsula. The latter reflects the concept of Peat et al. (2007) who divided the Antarctic continent into two major vegetation zones: the colder and drier Continental Antarctica (main part of the continent, eastern part of the Antarctic Peninsula) and the warmer Maritime Antarctica (west side of the Antarctic Peninsula north of about 72° S), which is in agreement with our results. The appearance of unexpectedly high precipitation values in the data caused a reevaluation of the whole computation. However, correctness of the data was confirmed by Sheng-Hung Wang of the Ohio State University (responsible for AMPS, pers. comm.). These high values account for only a fraction of data (0.14% of grid points in d2 and 7.03% in d6 reach values above 3000 mm a year) which is, without exception, located at the Antarctic Peninsula, more precisely, within d6.

The SD of the annual mean temperature reaches its maximum values in the Transantarctic Mountains and gets

smaller when using data with a better horizontal resolution, caused by the obviously heterogeneous and small-scale configuration of the landscape. The CV of the annual precipitation is maximal in those regions with very low precipitation. This is due to the definition of the CV: It is the ratio of the SD to the mean value. Thus, a CV of 1 simply means that the SD is the same as the mean value itself. Contrary to expectations, in contrast to the SD of the annual mean temperature, the CV of the annual precipitation gets higher when using data with a better horizontal resolution. Apparently, precipitation is very variable over the years. When averaging over an area of 10 × 10 km (as done in d2), those differences seem to even out, but when analyzing a smaller meshed grid (as done in d5 and d6), the variations over the years become clearer.

The temperature values of the meteorological stations and those computed from our model show a good match. Of course, a deviation of 6.60 °C translates into difference of up to two climate zones and requires additional more detailed consideration. These deviations might be partly due to the different time period that was taken into account (up to 96 years in reference data and only 7 years in our model), but predominantly, this divergence may be the result of (a) the interpolation process and (b) the resulting spatial resolution of 10 km, which still is quite coarse when deducing information for a single geographical point. This is supported by the fact that those stations that are located within d5 and d6 show smaller differences to the reference data than those in other regions.

The correlations show interesting patterns. In all three domains, higher elevation corresponds to lower temperature values, which is not surprising at all. This relationship is very strong for d2 and d5 and weaker for d6. Regarding latitude the exact opposite is the case: Again, all three domains point in the same direction, which means that higher temperature values correspond to increasing latitude. But in contrast to elevation, this relationship is very strong for d6 and much weaker for d2 and d5. Green et al. (2011a) also reported a strong linear relationship between latitude and annual mean temperature, which they noticed for 13 selected coastal climate stations ($r = 0.82$), a similar result as the $r = 0.85$ we obtained for the 30 climate stations used for the general evaluation of our temperature data. The weaker correlation ($r = 0.42$) between latitude and temperature of the whole Antarctic continent and its adjacent islands may be due to the fact that Antarctic meteorological stations in general are not evenly spread over the continent but predominantly located near to the coastline. Thus, the data of those stations cannot reflect the climate of the whole continent in a representative way. However, apparently, elevation is a better predictor for annual mean temperature than latitude, at least when analyzing the whole Antarctic continent.

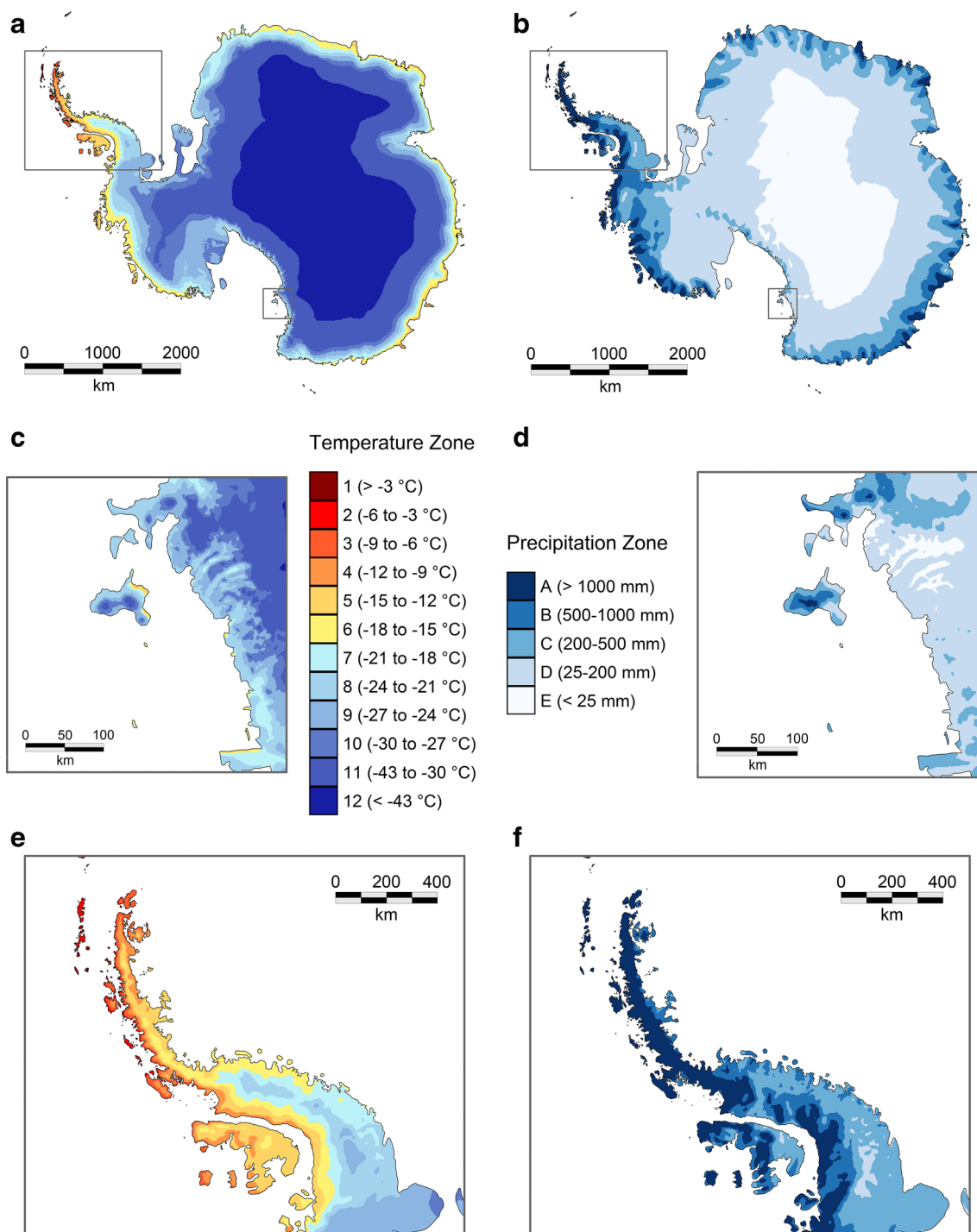
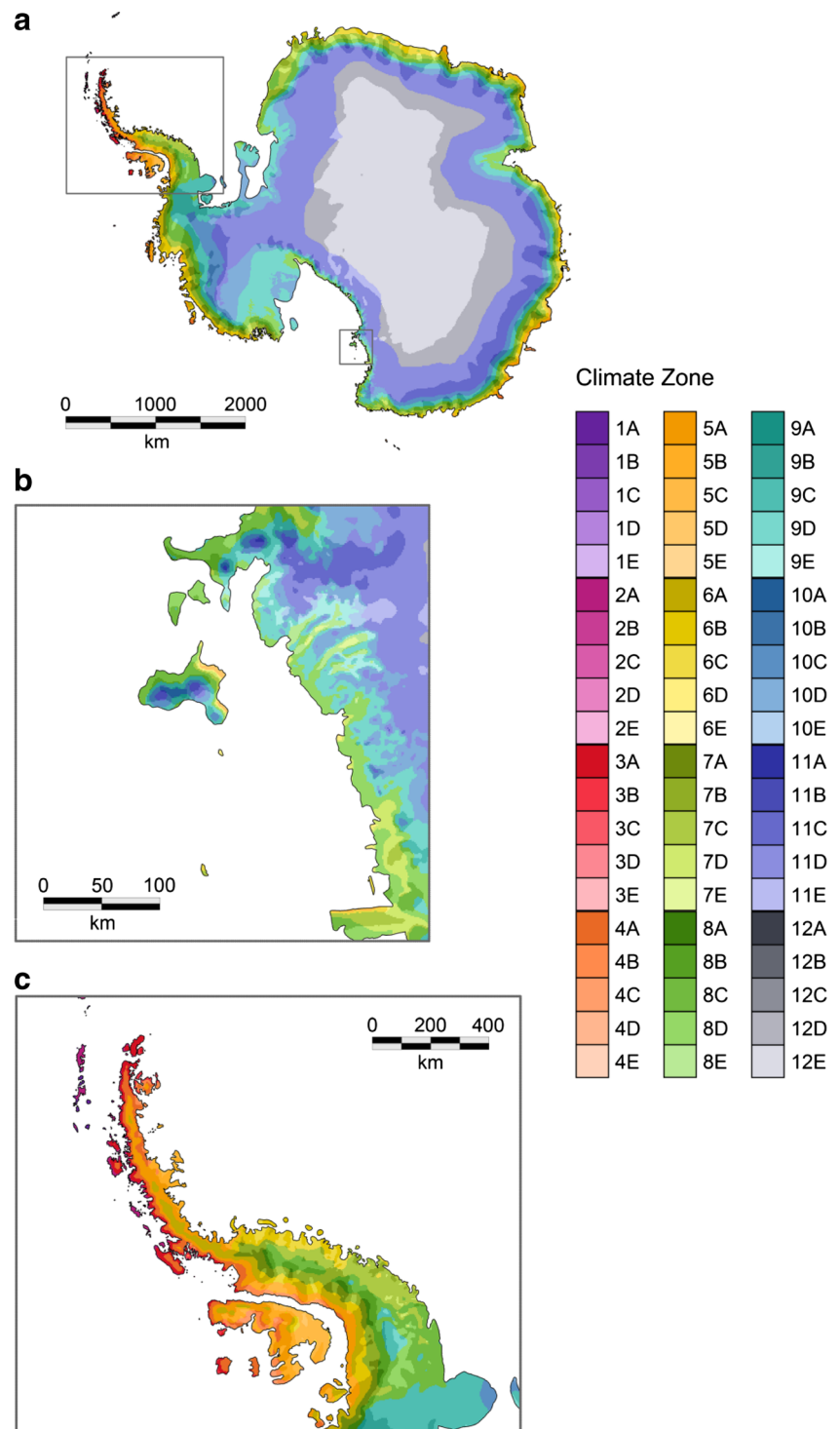


Fig. 9 Temperature zones (a, c, e) and precipitation zones (b, d, f) of Antarctic d2 (a, b), d5 (c, d), and d6 (e, f)

The comparison of the climate zones of the five different *Trebouxia* species shows the benefit of the present study: The climate classification, in the study of Ruprecht et al. (2012a) mostly based on subjective, verbal descriptions found in literature (Convey and McInnes 2005; Doran et al. 2002; Green et al. 2000, 2011b; Jones and Reid 2001; McKay et al. 1993; Monaghan and Bromwich 2008; Pannowitz et al. 2005; Reijmer and Van den Broeke

2001; Ruprecht et al. 2010; Seppelt et al. 1998; Simpson and Cooper 2002; Stickley et al. 2005), gets a better resolution and allows conclusions on a higher differentiated level when using the climate zones of the present study. The subjective evaluations of climate conditions can sometimes be quite misleading; the sample of *Trebouxia* sp. URa3 that was found in a habitat (Battleship Promontory, 76.9° S) assigned to the climate zone “I” by Ruprecht et al.

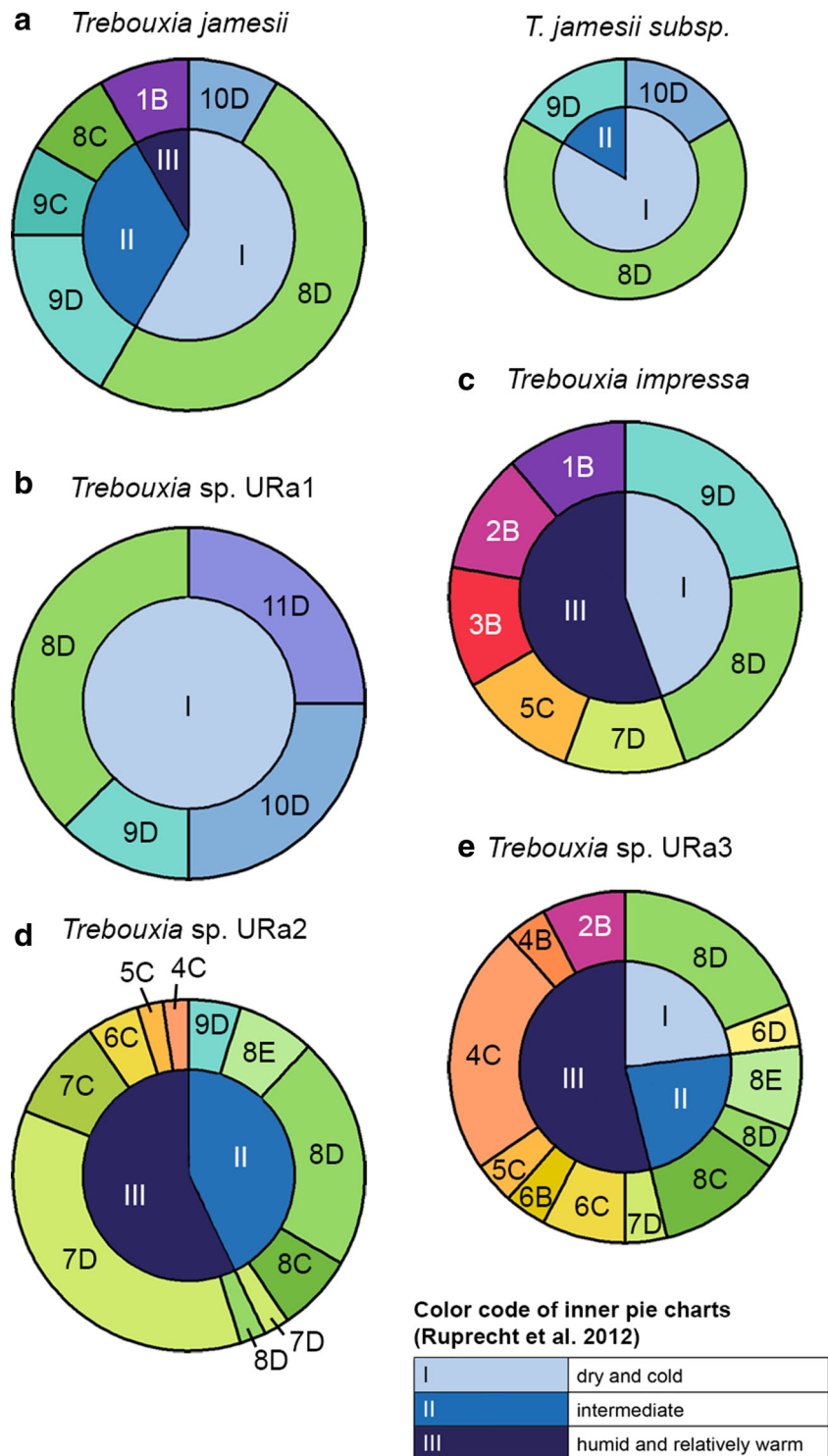
Fig. 10 Definition of climate regions by combining temperature and precipitation zones of Antarctic d2 (a), d5 (b), and d6 (c)



(2012a) and classified as 6D in our study (see Fig. 12) may illustrate that issue: This sample site was described as dry

and cold by McKay et al. (1993) and therefore was classified as zone “I” by Ruprecht et al. (2012a). However, in

Fig. 12 Distribution patterns of five different *Trebouxia* species (**a** *Trebouxia jamesii*, **b** *Trebouxia* sp. URa1, **c** *Trebouxia impressa*, **d** *Trebouxia* sp. URa2, and **e** *Trebouxia* sp. URa3) classified by climate zones. Inner pie charts refer to Ruprecht et al. (2012a); outer pie charts show the same samples classified by the climate zones of the present study



most likely caused by the use of different timescales and the changing environmental conditions in the years before 2009. However, in the context of Antarctic climate, one has to deal with some uncertainty: Climate change can both lead to warming (e.g., Vaughan et al. 2003; Turner et al. 2016) as well as cooling effects (summarized in Turner et al. 2005), and additionally, the seasonal variable size of the ozone hole is

connected to processes that have a large impact on the climate of Antarctica (Marshall 2016). The suggestion of Turner et al. (2016) that both the rapid warming since the 1950s and the subsequent cooling are within the bounds of the natural climate variability of the region reflects the complexity of the whole context. Presumably, further refinement of our modeled climate data over a longer time period can be expected to improve the

BIOCLIM variables and, as a consequence, the presented climate zonings. However, our model includes only 2 of the 19 BIOCLIM variables, which follows the special purposes of our study. Nevertheless, we highly encourage the users of our freely available database to design their own climate models following their own demands and maybe including some other variables that are relevant from a biological point of view.

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